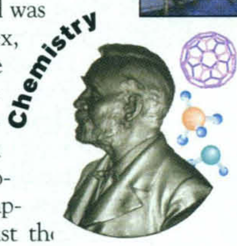
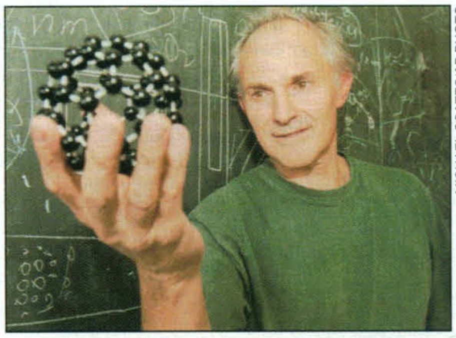
ered an entirely new class of all-carbon molecules shaped like intricate, spherical cages. Last week, the finding earned the team's leaders—Richard E. Smalley and Robert F. Curl Jr. of Rice University in Houston, and Harold W. Kroto of the University of Sussex in Brighton, United Kingdom—this year's Nobel Prize in chemistry. The discovery of "buckyballs" "[has] led to a completely new field of materials chemistry," says Charles Lieber, a professor of chemistry and applied physics at Harvard University. Today, researchers are investigating the all-carbon cages, also known as fullerenes, for use in applications ranging from new superconductors and catalysts to ultrasmall electronic devices.

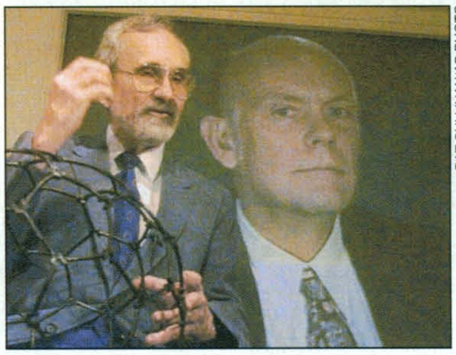
Prior to the discovery, researchers knew of only two naturally occurring forms of crystalline carbon. There was graphite, the gray "lead" in pencils, in which neighboring atoms are arranged in sheets of hexagons, and diamond, in which neighboring carbons are grouped into pyramids. Smalley, Curl, and Kroto set out to create a noncrystalline form—but what they had in mind was nothing like a buckyball. At Sussex, Kroto was studying star dust. He had theorized that the outer atmosphere of red giant stars would produce a bounty of long carbon chains and was interested in reproducing them in the lab. As it happened, Smalley and Curl had just the right equipment. Smalley had built a machine that vaporized materials with laser light in the presence of an inert gas, and they were using the apparatus to study how semiconductor and metal clusters grew out of the vapor.



Kroto learned of the cluster-building machine when he met Curl at a conference in the spring of 1984, and a year and a half later, their collaboration got under way. Shortly after the team began vaporizing carbon, the researchers and their graduate students, James Heath and Sean O'Brien, noticed a spike in the readings from their mass spectrometer, indicating that molecules with a combined mass of 60 carbons were forming in the vapor. Oddly, recalls Curl, "the peak was about 20 to 25 times as strong as the others." Even more oddly, when the researchers allowed the carbon clusters to cook in the machine with other molecules at high temperatures, the 60-carbon clusters proved to be "extremely unreactive," says Smalley.

That left them with a mystery. Sheets and pyramids of carbon are only stable when laced together in huge, continuous structures—a diamond, for instance. When a carbon structure has as few as 60 atoms, the many dangling bonds at the edges of the sheet or pyramid make the structure highly reactive. "We were looking for a structure of 60 carbon atoms that didn't want to react any further," says Smalley. That meant coming up with an architecture without dangling bonds.





Buckyboost. Kroto *(top)* with winning molecule. Curl *(above, left)* with Smalley *(above, right)* on screen.

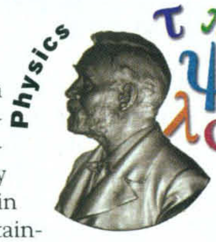
Near the end of their experimental run, the researchers hit on the crucial idea: that an arrangement of carbons in a pattern of hexagons and pentagons would cause the sheet to curl into a closed sphere. One night, Smalley stayed up late and built a paper model of a possible structure with a soccer-ball shape. The next morning, he showed it to his colleagues, and Curl and Kroto set out to determine if it obeyed the normal rules of carbon bonding. "I remember a shout for joy when they managed to do it," says Smalley. Within days they had submitted a paper on the topic to *Nature*.

Initially, many scientists were skeptical of buckyballs. But the structure was confirmed in 1990, when a team of physicists—led by Donald Huffman at the University of Arizona and Wolfgang Krätschmer from the Max Planck Institute for Nuclear Physics in Heidelberg, Germany—succeeded in synthesizing measurable quantities of fullerenes, which made it possible to study samples with structure-determining tools, such as x-ray diffraction machines.

Since then, the field has "exploded" into new areas, says Lieber, as researchers have discovered ways to both insert atoms into the cages and tack them onto the outside in an effort to make new materials with unique electrical, optical, and magnetic properties. Other teams are focusing on related tube-shaped fullerenes, called nanotubes, for possible uses in everything from tips for scanning probe microscopes to arrays of mini-electron guns for flat-panel displays. Says Marvin Cohen, a physics professor at the University of California, Berkeley, "There's so much action in the physics and chemistry of these things that we [will be] busy for a lot of years to come."

–Robert F. Service

A Cold Elixir for Physics



On the day before Thanksgiving in 1971, a graduate student in Cornell University's low-temperature laboratory monitored the pressure in a supercooled cell containing a mixture of liquid and solid helium-3. The pressure changed steadily as the temperature fell toward absolute zero, until it reached a few thousandths of a kelvin. At that point, the student—Douglas Osheroff, now a professor at Stanford University—noticed an unexpected shift in the rate of pressure change. Osheroff carefully reported the effect to his advisers, Cornell's David Lee and Robert Richardson. Months later the team realized what that shift had meant: It marked helium-3's transition from an ordinary fluid to a superfluid—a strange, frictionless, quantum-mechanical substance.

The finding struck low-temperature physics "like a lightning bolt," says Russell Donnelly of the University of Oregon. The lockstep atomic interactions required to make superfluid helium-3, says Philip Anderson, a theorist at Princeton University, meant the discovery "really was a milestone in our understanding of complex, many-body systems." The work's implications are still reverberating today, he says, in fields including cosmology and high-temperature superconductivity.

And in a recognition that Donnelly calls "way, way overdue," the discovery reverberated in yet another way in Osheroff's house in the wee hours of 9 October. "This fellow from Sweden called up, and I didn't recognize the accent. He said, 'Is Douglas Osheroff there?' I said, 'Yes, and it's 2:30 in the morning.' " Osheroff woke up quickly. Together with Lee and Richardson, he had won the 1996 Nobel Prize in physics.

The historical roots of the work go back well before 1971. A superfluid state of helium's most common isotope, helium-4, was first produced in 1938 by cooling it to about 2.2 K. The relatively accessible temperature of the helium-4 transition reflects the rules of quantum mechanics. The quantum-mechanical spins of the protons, neutrons, and electrons in each helium-4 atom add up to an integer value. That qualifies the atoms as "bosons," meaning they can all drop into the same low-energy state and move in lockstep. If the flow is gentle enough, the atoms can't absorb enough energy to jump to the next higher state—meaning that they can't absorb any energy from the flow at all, making it frictionless. This lets the fluid flow without viscosity through tiny fissures and up the sides of containers.

Helium-3 atoms, with one fewer neutron and a half-integer spin, are "fermions," subject to rules that forbid any two of these atoms from being in the same state. Atoms can slosh around in the resulting sea of different energy states, exchanging energy and causing friction. But in 1956, John Bardeen, Leon Cooper, and Robert Schrieffer (BCS) explained the lack of electrical resistance in low-temperature superconductors by showing that spin-1/2 electrons can pair off and act like bosons. Shortly afterward, says Anthony Leggett, a theorist at the University of Illinois, Urbana-Champaign, "a whole lot of people predicted that helium-3 should become superfluid by the same mechanism."


PAUL SAKUMA/AP PHOTO


DENIS PAQUIN/AP PHOTO


MICHAEL OKONIEWSKI/AP PHOTO

Superfluid helium's three. Osheroff *(top left)*, Richardson *(above)*, and Lee.

Unfortunately, says Leggett, just how the helium-3 pairing should occur was uncertain, so that the predicted temperature of the transition "bounced around" and eluded numerous experimental searches. The Cornell effort, originally designed to search not for superfluidity but for magnetic anomalies in solid helium-3, stumbled on the pressure glitches by luck. As it turned out, they marked a series of superfluid phase transitions in the liquid helium-3.

The team eventually uncovered three different superfluid phases with much more complex pairing structures than those envisioned in BCS theory. Because the cooperative interactions among the pairs of atoms waltzing through the liquid leave a magnetic signature, the team was able to unravel some of these interactions using nuclear magnetic resonance, a technique they were skilled in. Such work took "8 months of solid experimentation," says Lee. "It was a very enjoyable period. One beautiful thing after another happened in the laboratory."

The novel pairings, says John Ketterson of Northwestern University, "make for a very rich structure that initially surprised a lot of folks." For example, says Ketterson, superfluid helium-3 has bizarre modes of oscillation that have no counterpart in normal fluids, and its pairing mechanisms may serve as models for understanding how electrons pair up in high-temperature superconductors, which are still mysterious. With those kinds of riches to explore, it's no surprise that "a whole generation of students studied the material for the next 20 years" after its discovery, says Ketterson. "And people like me are still doing it."

–James Glanz

WINNING INCENTIVES FOR TRUTHTELLING

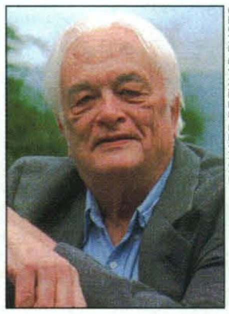
The 1996 Nobel Memorial Prize in Economic Science was awarded to William Vickrey and James Mirrlees for their studies of humans and the truth: how to get people to tell the truth in economic transactions, and what to do when they don't. In related lines of work that Robert Wilson of Stanford University's graduate school of business calls "fundamental and useful," Vickrey and Mirrlees have changed how economists and businesspeople structure everything from contracts to taxes and auctions.

Vickrey, who died suddenly last week, and Mirrlees opened up the study of "informational asymmetries"—situations in which people on different sides of a transaction have incomplete and differing information. In the mid-1940s, Vickrey, who was a professor emeritus at Columbia University, explored the effects of these asymmetries on taxation. He pointed out that the government has incomplete information about incomes, which is why people can cheat on their taxes. He also noticed that taxes can have the effect of lowering people's productivity by reducing their incentive to work. People offered a promotion may have less incentive to take the new job if it catapults them into a higher tax bracket.

Vickrey made great headway in designing an optimal income tax which wouldn't reduce incentives to work and would distribute the tax burden fairly. But it fell to Mirrlees a quarter century later to sort through the problem's complicated mathematics. In 1971, Mirrlees, currently a professor at Cambridge University, devised a new analytic method that simplified drastically the mathematics of not only Vickrey's optimal tax problem, but a host of other tough economic problems where parties don't share the same information. According to Avinash Dixit, professor of economics at Princeton University, "[Mirrlees's ideas] have provided the basis for almost all the subsequent progress in areas as diverse as taxation, regulation, contracts, and auctions." Indeed, Mirrlees's methods soon gave rise to the "revelation principle," which states that the solution to an incentive problem with informational asymmetries is to set up a situation in which it is to everyone's advantage to disclose private information—truthfully.

Back on the other side of the Atlantic, Vickrey had discovered how to do just that—at least in auctions. In an ordinary sealed-bid auction, people often have little incentive to bid an object's true value: Objects go to the highest bidder, and, in general, buyers deflate bids, hoping to get a bargain. Only in bidding wars do people reveal what they are truly willing to pay. In the early 1960s, Vickrey solved the problem when he came up with the "second-price" auction, now called a Vickrey auction. This scheme awards the object to the highest bidder—but she pays only the amount of the second-highest bid. Thus, a bidder has a strong incentive to bid the object's true value: She knows up front she won't have to pay her full offer, and if she submits a low-ball bid and loses, her competitor winds up getting a big price break.

Vickrey's and Mirrlees's work has had an enormous impact on the business world. The recent Federal Communications Commission auction of bandwidth was a direct descendant of the Vickrey auction, for instance. The federal government is also beginning to experiment with an application of the revelation principle known as a uniform price rule in auctions of treasury bills. Instead of auctioning off T-bills in the standard way, the government combines bids to determine demand. They then sell the entire lot at the same "uniform" price. According to Stanford's Wilson, the design of the deregulation of one of America's biggest industries—the power industry—is also based upon principles founded by Mirrlees and Vickrey. Soon, generators, power plants, and raw materials will go on the block.


RICHARD DREW/AP PHOTO


FINDLAY KEMBER/AP PHOTO

Honesty honored. Vickrey *(left)* and Mirrlees *(right)* revolutionized auctions.

–Charles Seife

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